# Modified UTC photodiodes on silicon for low-power high-speed applications

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# Introduction

**High-speed high-efficiency (=responsivity) photodiodes are key components in low-power optical interconnects.**

- **Reduced photodiode (PD) capacitance benefits high-speed PD – transimpedance amplifier (TIA) and enables 'amplifier-free' front end.**
- **Operate photodiode at low bias: low dark current and minimized (standby) power consumption.**
- **Integration on silicon photonics platform**

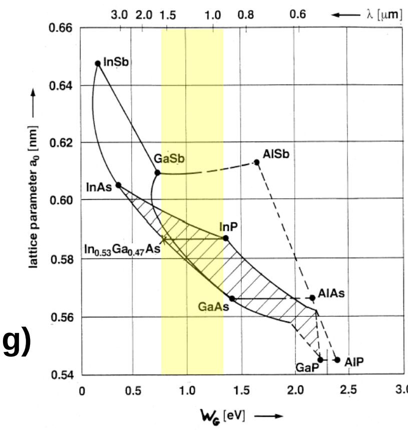
**High-speed InGaAs/InP modified uni-traveling carrier (MUTC) photodiodes on silicon:**
**- Wafer bonded MUTC PD on silicon-on-insulator (SOI) waveguide**

**- Back-illuminated MUTC PD on Si using adhesive wafer-bonding**

**- MUTC PD on silicon using direct epitaxial growth**

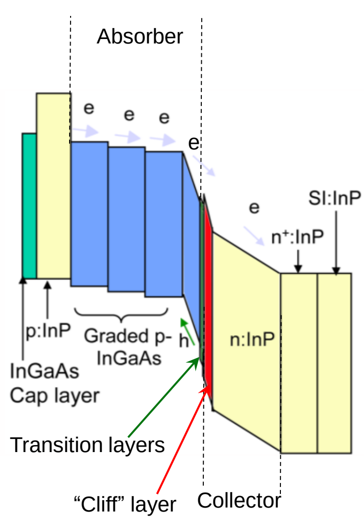
# InP-Based Photodiodes

- **High material quality: low dark current.**
- **Direct bandgap: large absorption**
- **Lattice-matched compounds InGaAsP, AlGaInAs: absorptive and transparent layers between 1.65 μm and 0.92 μm (Bandgap Engineering)**
- **High electron drift velocity: High speed >100 GHz.**

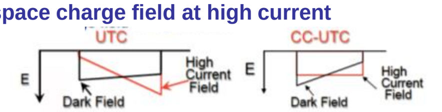




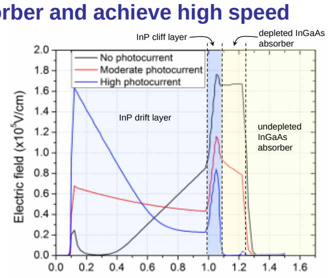

## Charge-Compensated Modified Uni-Traveling Carrier PD (MUTC PD)




**1. Charge compensated collector to suppress space charge field at high current**



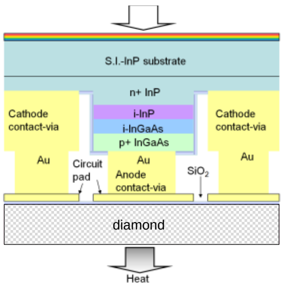

**2. "Cliff" layer to maintain high field in depleted absorber and achieve high speed**

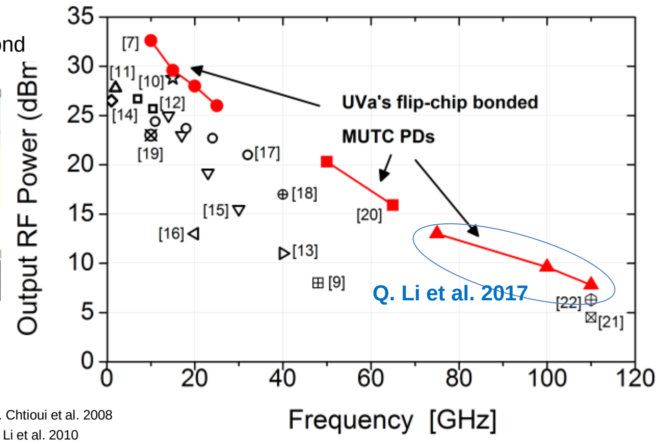



**3. Partially depleted absorber - Maintain high field across heterojunction interface - Increase responsivity without sacrificing speed**

## Discrete MUTC Photodiodes: RF Output Power

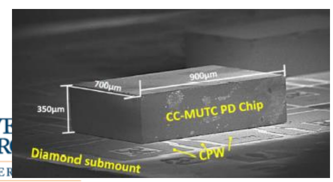
Flip-chip bonded on diamond



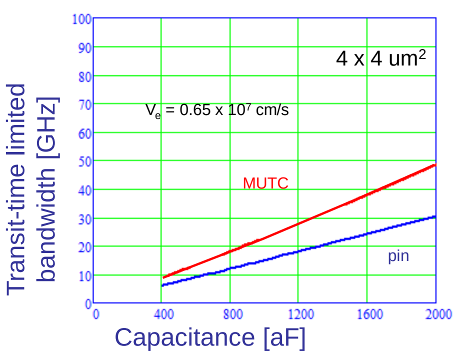


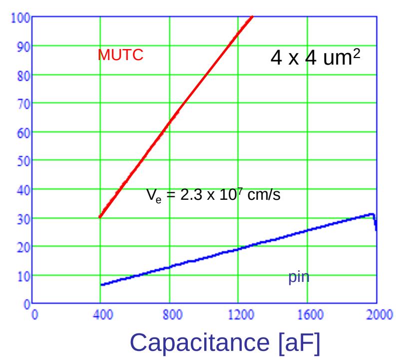
[7] X. Xie et al. 2014
[9] X. Li, et al. 2003
[10] Z. Li et al 2013
[11] N. Duan et al. 2006
[12] K. Sakai et al. 2010
[13] N. Shimizu et al.2000
[14] D. A. Tulchinsky et al. 2008
[15] X. Wang et al. 2007
[16] M. Chtioui et al. 2008
[17] Z. Li et al. 2010
[18] n. Li et al. 2004
[19] M. Chtioui et al. 2012
[20] Q. Zhou et al. 2013
[21] A. Stöhr et al. 2010
[22] Y.-S. Wu et al. 2008




## Capacitance: MUTC vs. p-i-n



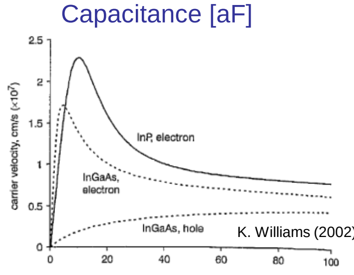




$$BW = \frac{3.5\, v}{2\,\pi\, d} \qquad C_{pn} = \frac{\varepsilon_0 \varepsilon_r A}{d}$$

A: PD area

d: depletion width

v: carrier velocity

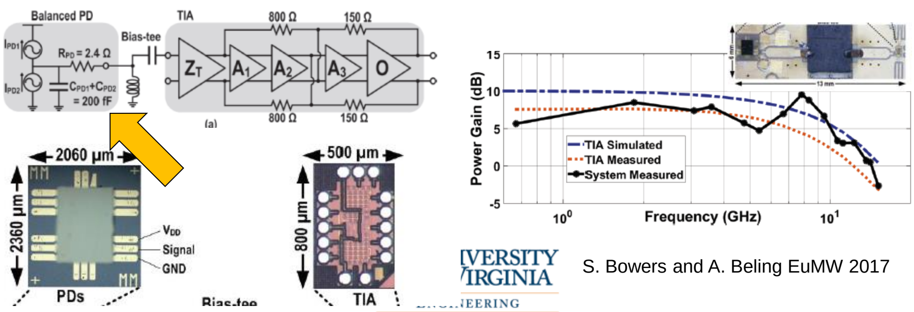



K. Williams (2002)

# Low-Capacitance Photodiode

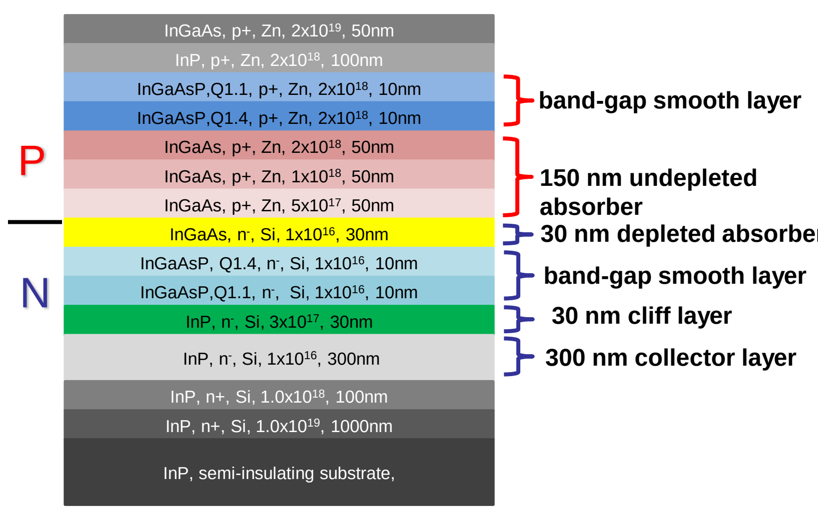
- **A receiver-less optical front end (w/o amplifier) becomes feasible (D.A.B. Miller, M. Wu, Nozaki, NTT)**
- **In PD – TIA front end:**
  **bandwidth, noise, and power consumption frequently benefit from smaller PD capacitance.**

Balanced PD w/ 130 nm CMOS TIA:




S. Bowers and A. Beling EuMW 2017

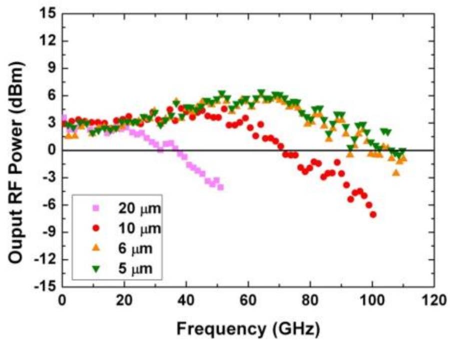
# 100 GHz MUTC PD Epi-Layer Design

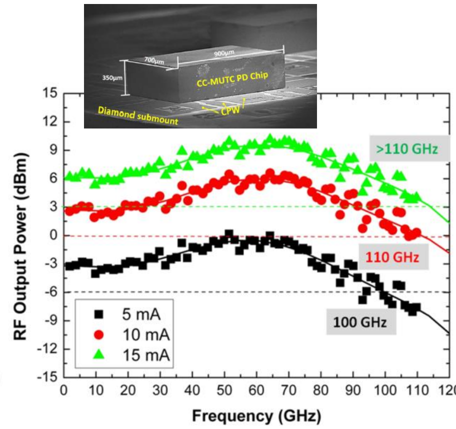



Q. Li et al., *IPC 2015*

# Bandwidth

**PDs with different areas at 10 mA and 4 V:**



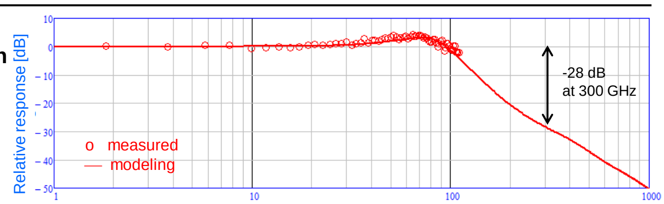

**Responsivity: 0.17 A/W**

**Bandwidth-efficiency product: 15 GHz**

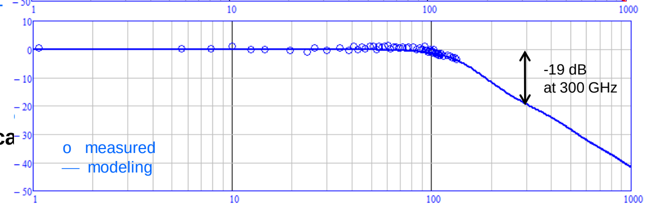


# Frequency Response 5-μm diameter PD

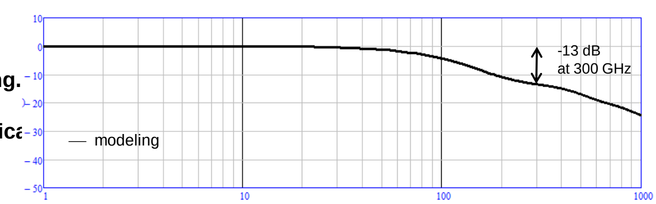
**Previous submount with inductive peaking.**
**208 pH**




**New submount with reduced inductive peaking.**
**105 pH**
**(all other parameters identica**

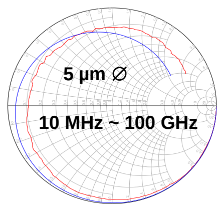



**Proposed submount with negligible inductive peaking.**
**4 pH**
**(all other parameters identica**



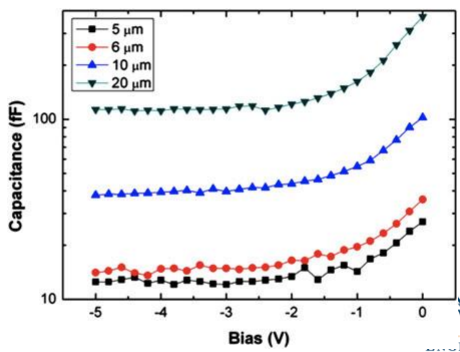
# PD Capacitance

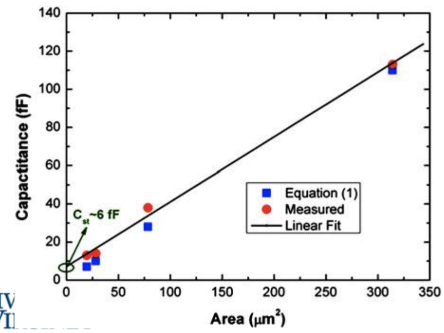
Measured and fitted S11 data




MEASURED AND CALCULATED PARAMETERS

| Diameter (μm) | Eq.(1) $C_{pn}$ (fF) | Measured $C_{pn}$ (fF) | Extracted from S11 fitting | | |
|---|---|---|---|---|---|
| | | | $C_{pn}$ (fF) | $R_s$ (Ω) | $L_s$ (pH) |
| 5 | 7 | 7 | 6 | 6 | 90 |
| 6 | 10 | 8 | 8 | 6 | 86 |
| 10 | 28 | 32 | 27 | 6 | 70 |
| 20 | 110 | 107 | 106 | 5 | 65 |

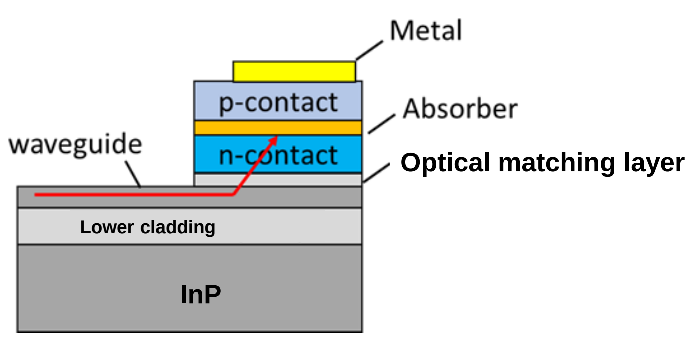



Q. Li et al., *JLT 2016*

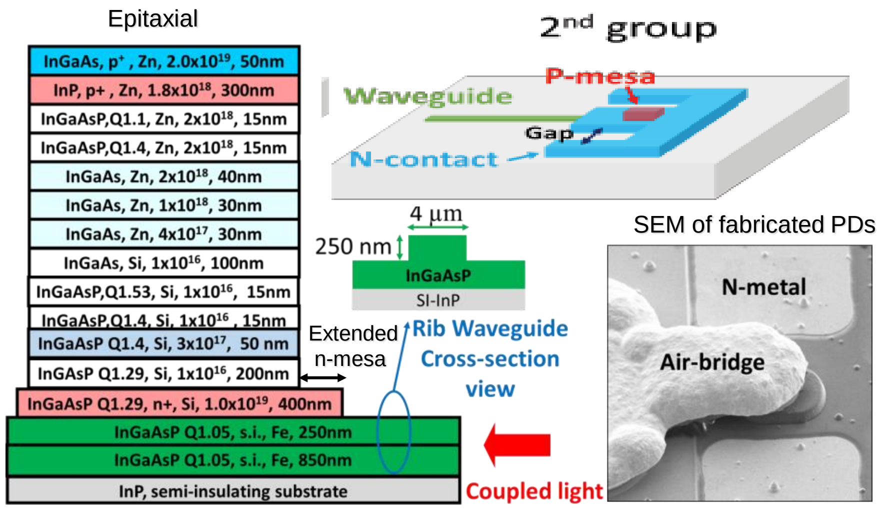
# Waveguide MUTC PD

**Higher Bandwidth-Efficiency product since responsivity and transit-time limited bandwidth are decoupled.**




**Key component in photonic integrated circuits (PICs).**

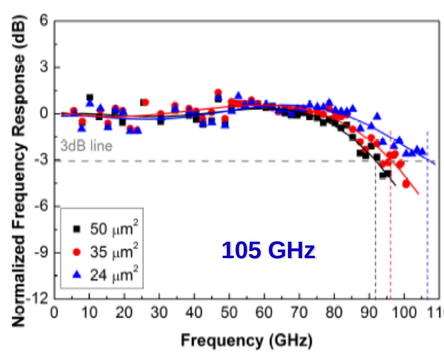
## Design Waveguide MUTC Photodiode





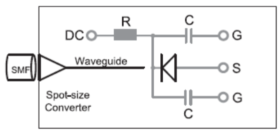

## High-Speed Waveguide MUTC PD

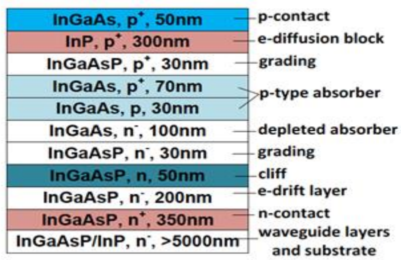
| Size ($\mu m^2$) | R (A/W) | | |
|---|---|---|---|
| | External R | Internal R | Simulated Internal R |
| 24 | 0.1 | 0.35 | 0.38 |
| 35 | 0.12 | 0.42 | 0.48 |
| 50 | 0.15 | 0.52 | 0.64 |

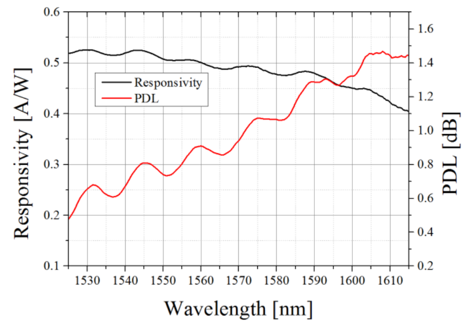



- **105 GHz bandwidth and 0.35 A/W**
- **30 GHz bandwidth-efficiency product**

## Waveguide MUTC PD



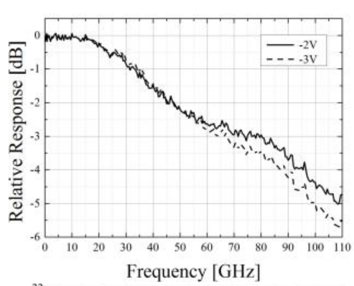



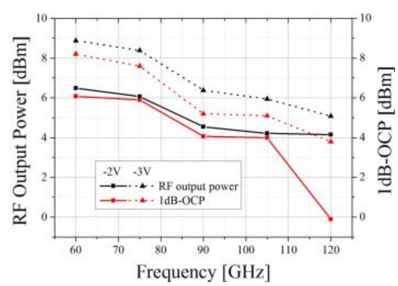



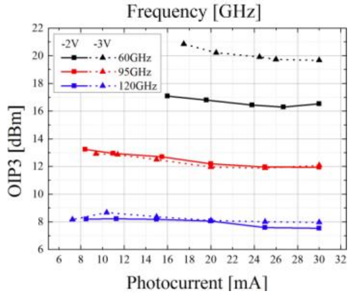

**Fiber-coupled responsivity: 0.5 A/W**



## Waveguide MUTC PD



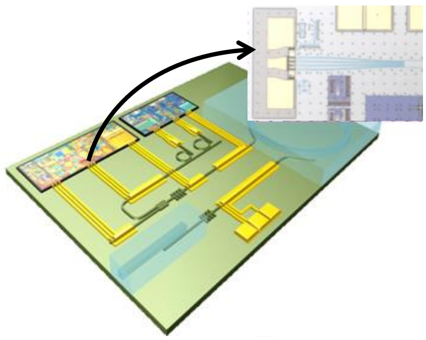

**Bandwidth: 80 GHz**

**High linearity: Output third-order intercept (OIP3): 20 dBm @60 GHz**

**Bandwidth – efficiency product: 32 GHz**

## Heterogeneously Integrated III-V Photodiodes on Silicon

**With the rapid progress in Si photonics there has been increased interest in silicon-compatible high-performance waveguide photodiodes that operate at the long telecommunication wavelengths.**



**Heterogeneous integration:**
- **bandgap engineering**
- **absorption in C- and L-band**
- **low dark current**
- **high dynamic range, high-linearity**

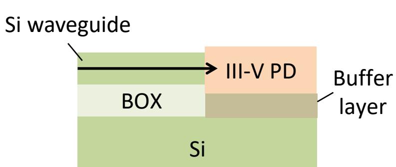
**Make InP-based devices available to large-scale integrated circuits on a silicon photonics-electronics platform for applications in communications, optical interconnects, and microwave photonics.**





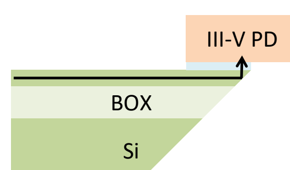
## Integration Schemes

**Butt-coupled to SOI waveguide:**



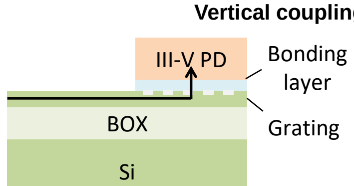

**Selective-area growth (MOCVD) on InP/GaAs buffer.**
$I_{dark}$ = 400 μA (5 V), BW = 15 GHz.
(Geng et al. 2014)

**Etched or polished reflective mirror:**




Vertically illuminated PD attached to waveguide by **epoxy**.
IL = 5 dB, BW = 28 GHz.
(Zimmermann et al. 2012)

**Vertical coupling grating:**

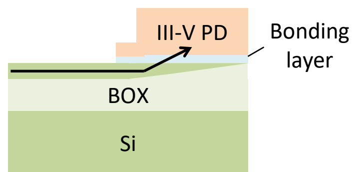



**Adhesive bonding with BCB or epoxy**
$I_{dark}$ (1 V) = 0.3 nA, R = 0.02 A/W.
(Roelkens et al. 2005)

# Integration Schemes (2)

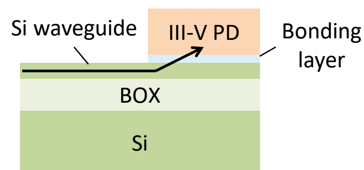
**Direct (molecular) bonding or adhesive bonding:**

**Adiabatic taper:**




Tapered InP membrane input waveguide
BW = 33 GHz R = 0.45 A/W.
(Binetti et al. 2010)

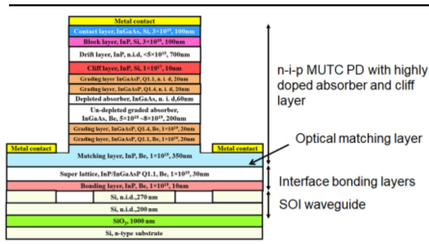
**Evanescent coupling:**

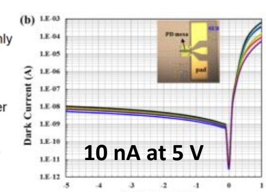


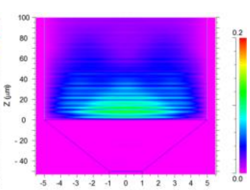

Quantum well p-i-n PD.
$I_{dark}$ = 100 nA (2 V), R = 0.31 A/W.
(Park et al. 2007)



# 40 GHz High-Power PD on SOI

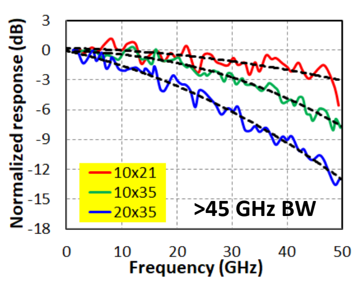


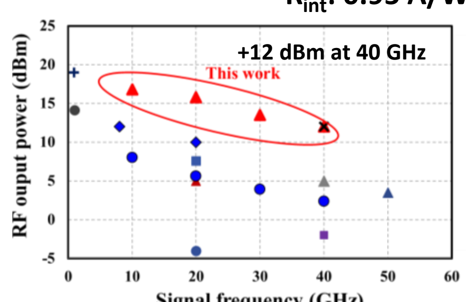



**$R_{int}$: 0.95 A/W**

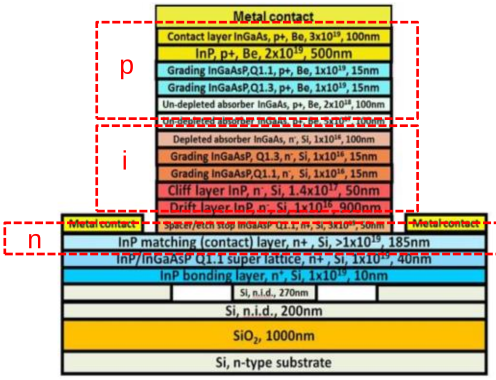
III-V epi structure is transferred to the patterned Si through low-temperature oxygen-plasma-assisted wafer bonding (UCSB/Aurrion process).

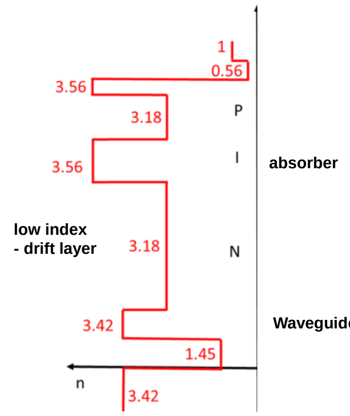



Xie et al. OFC 2015 PDP

## Heterogeneous PD on SOI with inverted layer structure




**PD with p-contact on top:**
1) **Better process compatibility**
2) **Lower heat resistance by placing heat source close to SOI substrate**
3) **High n-type doping levels can be achieved in InP (>1e10$^{19}$ cm$^{-3}$)**

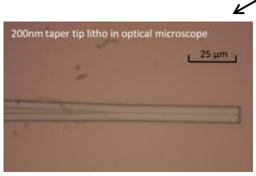
**Issue: Evanescent coupling through low index drift layer is not efficient.**

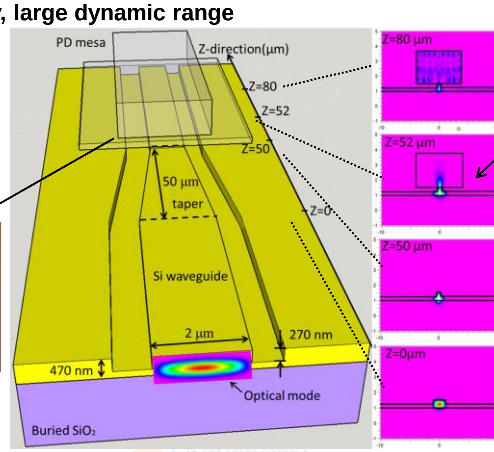


## PD on SOI Nano-Waveguide

**Heterogeneous integration: Ability to independently change the widths of the Si waveguide and the III-V mesa to engineer the absorption profile.**
- **Si nano-waveguide: Engineer the confinement factor for optimum absorption profile**
- **High efficiency, large dynamic range**

**Nano-waveguide before III-V bonding**

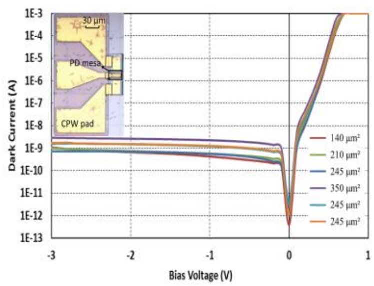


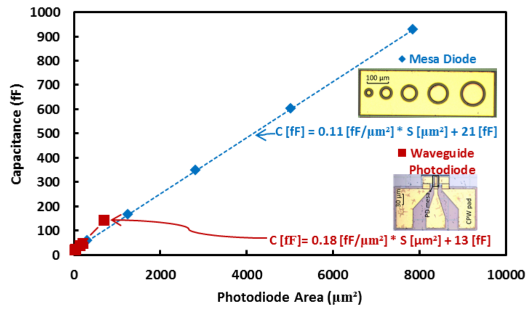




**Weakly confined mode couples into mesa PD**

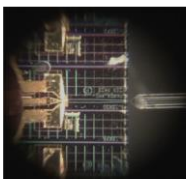
Wang et al. IPC 2016

# PD Characterization




Dark current: 1 nA at -3 V



Internal responsivity at 1550 nm:
0.84 A/W for 50 µm-long PD

Pad capacitance 13 fF

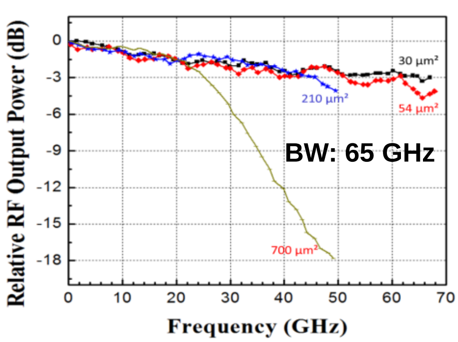
Junction capacitance for a PD with 30 µm$^2$ area is only 5 fF.

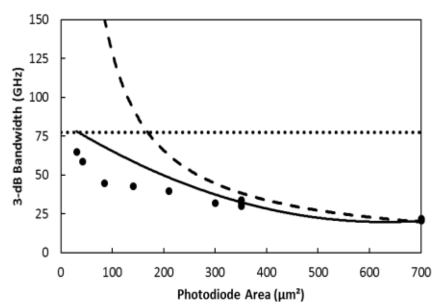
Photonics West 2018

University of Virginia Engineering

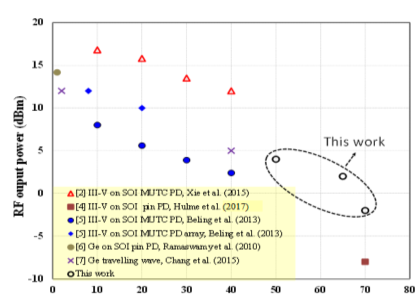
Wang et al. JSTQE 2018 23

# PD Characterization



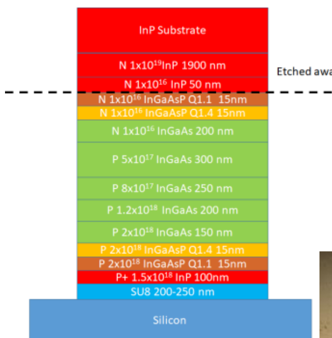

Bandwidth: 65 GHz
Large dynamic range:
20 mA photocurrent

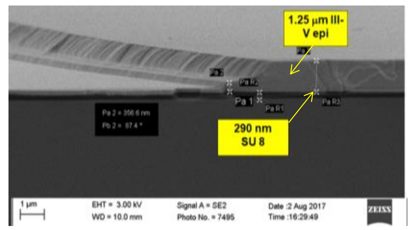


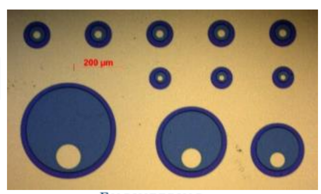

Photonics West 2018

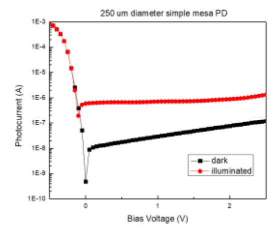
## Heterogeneous integration on Si using adhesive bonding

- **III-V PD on Si using low-temperature adhesive bonding (SU8) process**
- **SU8 layer thickness is only 290 nm (will work for waveguide PDs)**
- **MUTC-structure bonded, substrate removal, low-dark current top-illuminated PDs fabricated**



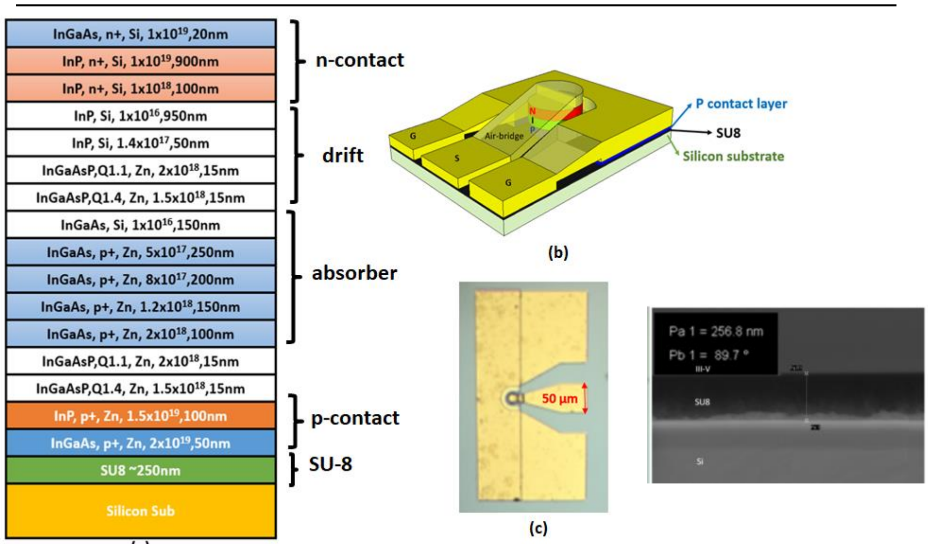





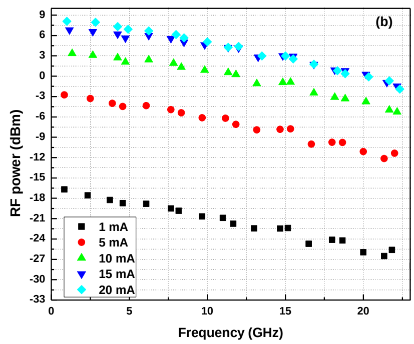


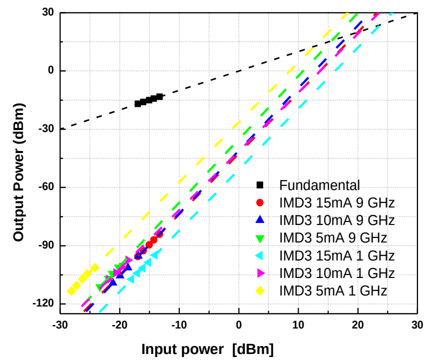

# Back-illuminated MUTC PD on Si




(a) (b) (c)

# Experimental Results




- **0.48 A/W responsivity at 1550 nm (no ARC)**
- **Bandwidth: 18 GHz**
- **OIP3 up to 28.5 dBm**

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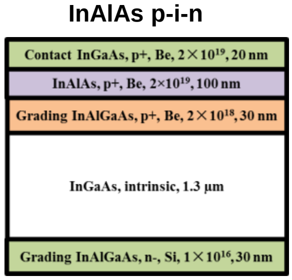
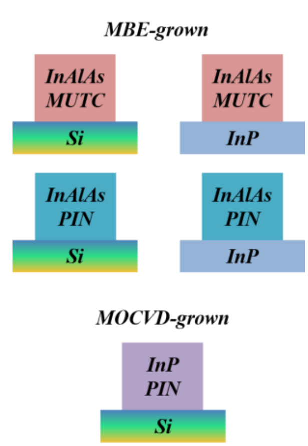
# PD III-V epi-structures grown on Si

**InAlAs p-i-n**

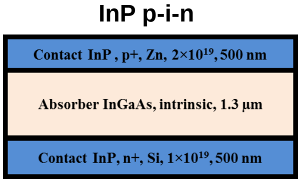



**InAlAs MUTC**

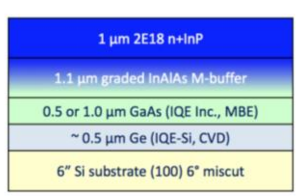

*MBE-grown*



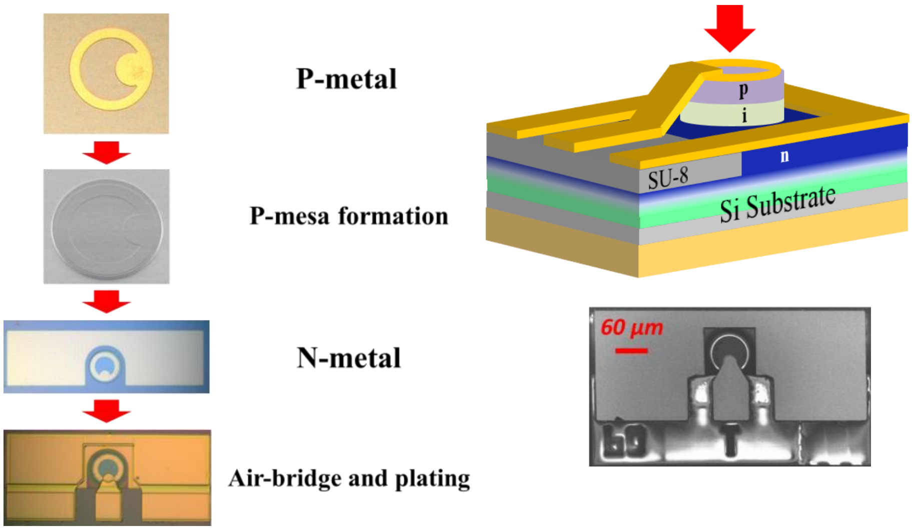

**InP p-i-n**




**Si template**

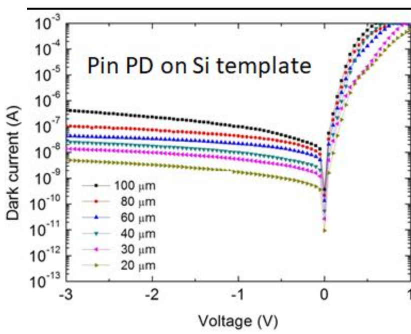


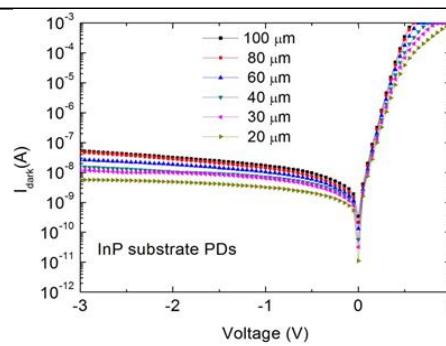
# PD fabrication

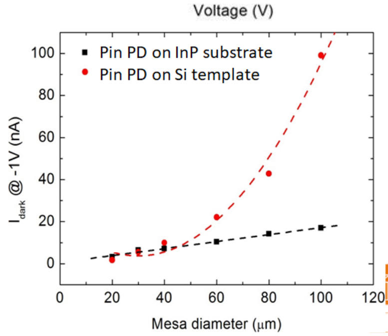





# Results



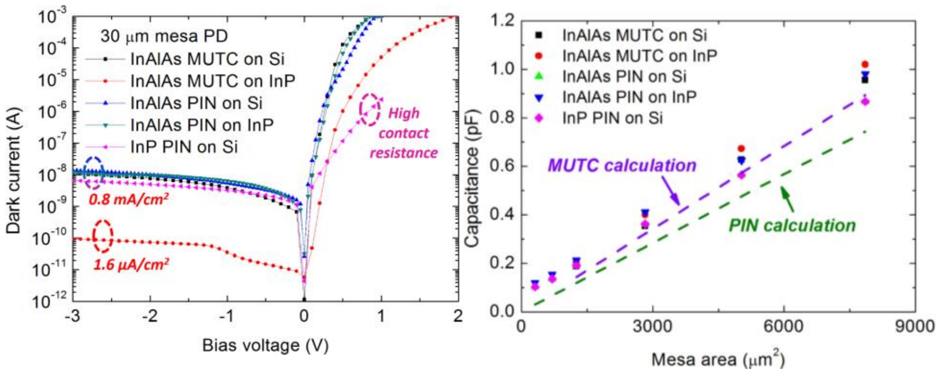




- **Dark current as low as 4 nA at -3 V.**
- **No difference to PDs grown on native InP substrate**
- **Dark current density: 1.3 mA/cm$^2$**

Sun et al. IPC 2017

# Dark I-V and C-V

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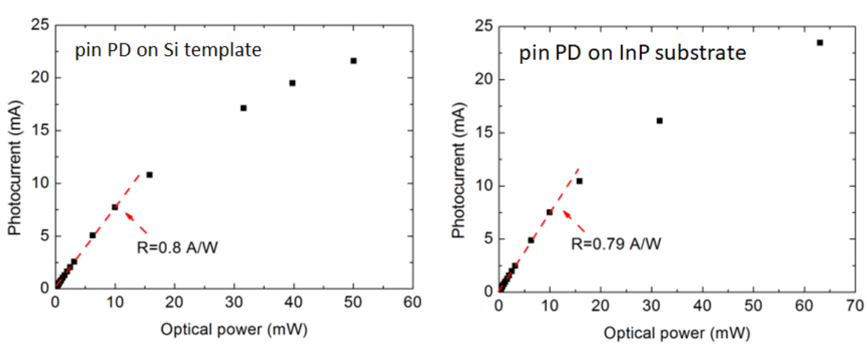
# Responsivity




- **0.8 A/W at 1550 nm**
- **No difference in responsivity between p-i-n on Si and p-i-n on InP**

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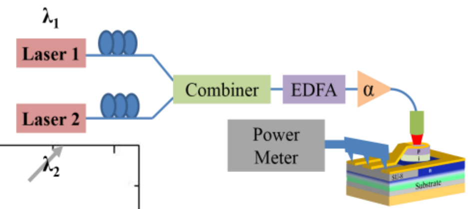
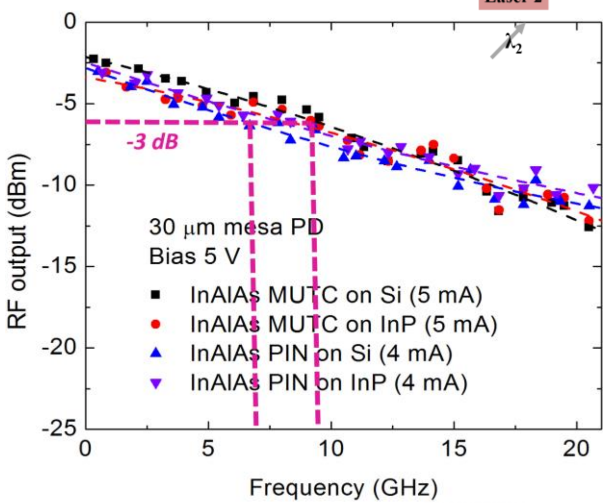
## Bandwidth




**Bandwidth: 9 GHz**

**Limited by high (ring-) contact resistance.**

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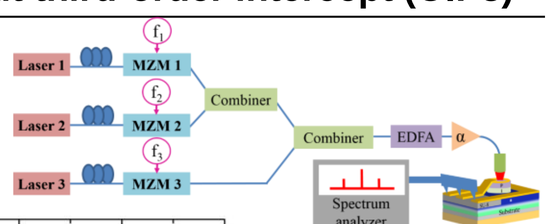
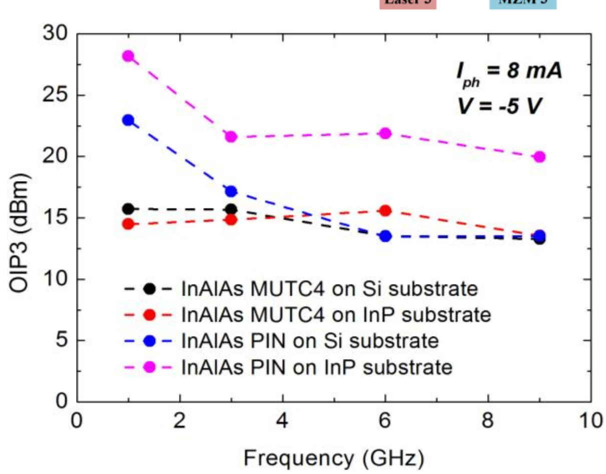
## PD linearity: Output third-order intercept (OIP3)




**OIP3 > 15 dBm.**

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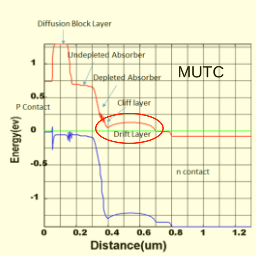
## Overview top-illuminated PDs on Si

TOP-ILLUMINATED PDs ON SI REPORTED IN THE LITERATURE.

| Ref. | $I_{dk}$ (mA/cm$^2$) | R (A/W) | BW (GHz) | $P_{sat}$ (dBm) |
|---|---|---|---|---|
| This work | **1.3** | 0.79 | 9 | 2.6 @ 9 GHz |
| [6] | 40 | 0.6 | 14 | NA |
| [9] | 57 | 0.18 | 10 | 3.7 @ 3 GHz |
| [20] | 82 | 0.12 | 20 | 1.7 @ 20 GHz |
| [21] | 20 | NA | 29 | NA |
| [22] | 100 | 0.035 | 39 | NA |
| [23] | 2 | 0.036 | 15 | NA |
| [24] | 100 | 0.07 | NA | NA |
| [25] | 1989 | 0.62 | 21.5 | NA |
| [26] | 484 | 0.73 | 12 | NA |
| [27] | 382 | 0.7 | 39 | NA |
| [28] | 6 | NA | 9 | NA |

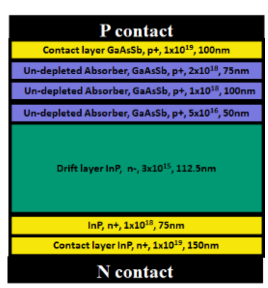


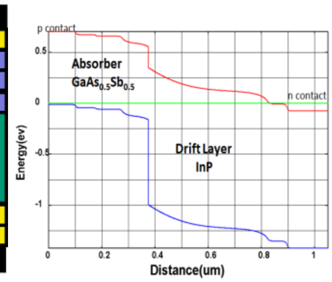
## Outlook: Zero-bias $GaAs_{0.5}Sb_{0.5}$/InP MUTC




MUTC bandwidth limitations at low bias:

- Drift layer not (fully) depleted
- Band discontinuities at heterointerface




- **Eliminates band discontinuities**
- **Moderate E-field causes velocity overshoot**
- **Highest BW at 0 V**

# Summary & Acknowledgment

- High-efficiency photodiodes on both, InP and SOI, up to 105 GHz bandwidth have been demonstrated.
- Waveguide PDs on SOI: Low dark current 1 nA, low capacitance 5 fF, high responsivity 0.84 A/W, and bandwidth up to 65 GHz
- InGaAs/InP photodiodes on silicon using direct epitaxial growth have dark current density of 1.3 $mA/cm^2$ and a responsivity of 0.8 A/W.

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